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Satellite-based herbicide rate recommendation for potato haulm killing

Frits K. van Evert[a,*], Paul van der Voet[b], Eric van Valkengoed[b], Lammert Kooistra[c], Corné Kempenaar[a]

[a] Plant Research International, Wageningen University and Research Centre, PO Box 616, 6700 AP Wageningen, The Netherlands
[b] TerraSphere Imaging & GIS, Keizersgracht 114, 1015 CV Amsterdam, The Netherlands
[c] Laboratory of Geo-information Science and Remote Sensing, Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen, The Netherlands

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ABSTRACT

When using variable-rate application (VRA), tractor-mounted sensors are typically used to measure crop status. Crop status can also be measured with a satellite-based sensor. In both cases a vegetation index derived from the sensor measurements is used as an indicator of the amount of crop biomass. The first objective of this study was to establish a relationship between the Weighted Difference Vegetation Index (WDVI) in potato as measured with a nearby, ground-based crop reflectance meter on the one hand and WDVI as measured with remote, satellite-based sensors on the other hand. It was found that ground-based WDVI and satellite-based WDVI are strongly and linearly related, thus making it feasible to calculate herbicide rates for potato haulm killing on the basis of satellite-based measurements. The scale at which VRA is applied is an important determinant of the reduction in input use. The second objective was to estimate the potential to reduce herbicide use for potato haulm killing as a function of the size of decision units, using the above-mentioned relationship, satellite imagery of 13 potato fields and a previously developed decision rule for herbicide rate. It was found that when the size of the decision unit was 15 m × 15 m (the size of an ASTER pixel), a reduction in herbicide use of at least 50% would be achieved in one out of every two of the fields, and a reduction of at least 33% would be achieved in all fields. When the size of the decision unit was 30 m × 30 m, a reduction of at least 33% would be achieved in one out of every two of the fields. In conclusion, satellite-based crop reflectance measurements can be used instead of ground-based measurements for determining herbicide rate for potato haulm killing. When the size of the decision unit is not larger than 30 m × 30 m, a 50% reduction in herbicide use for potato haulm killing can be achieved with VRA.

1. Introduction

Potato (*Solanum tuberosum* L.) haulm killing (PHK) is a routine practice, employed mainly to allow mechanized harvesting of tubers with desired qualities (specific size, content, no infections; Kempenaar and Struijk, 2008). A commonly used herbicide for chemical PHK is diquat dibromide, at a rate of 600–800 g ha^{-1}. Herbicides used for potato haulm killing present an environmental burden. However, the amount of herbicide needed for effective haulm killing depends on the vitality of the potato crop at the time of herbicide application, thus a herbicide rate less than the nominal rate may suffice when the crop has already partially died off. Crop vitality at the end of the season varies with weather, crop management, variety, and the time of harvest. A reduction in herbicide use may also be achieved by exploiting site-specific variation. Site-specific variation in yield and crop vitality is generally large in a potato crop, and it can be quite pronounced towards the end of the growing season. Site-specific variation in vitality of a potato crop is exploited by variable-rate application (VRA) systems, such as N-Sensor MLHD PHK and SensiSpray, to reduce the amount of herbicide needed for haulm killing (Kempenaar and Struijk, 2008; Kempenaar et al., 2010b; Michielsen et al., 2010) (see also www.precisielandbouw.eu). These systems use a tractor- or sprayer-mounted crop reflection meter (near-sensing) to assess the vitality of the crop and then use a decision rule to determine the required herbicide rate on-the-go. Vitality of the crop is measured by means of a vegetation index. Specifically, the Weighted Difference Vegetation Index (WDVI) (Clevers, 1989) has been found to be a good indicator of the vitality of a potato crop. It has been reported that savings up to 50% relative to current practice are possible, with effectiveness of the treatment unaffected (Kempenaar et al., 2004).

Despite the success of VRA PHK, two questions loom over the practical application of the system. The first question relates to the

Abbreviations: VRA, variable-rate application; PHK, potato haulm killing; WDVI, Weighted Difference Vegetation Index (subscript "sat" denotes measurement with a satellite, subscript "cs" denotes measurement with a Cropscan reflectance meter); S1, (proprietary) vegetation index produced by the Yara N-Sensor.

* Corresponding author. Tel.: +31 317 480573; fax: +31 317 481047.
E-mail addresses: frits.vanevert@wur.nl (F.K. van Evert), paul@terrasphere.nl (P. van der Voet), eric@terrasphere.nl (E. van Valkengoed), lammert.kooistra@wur.nl (L. Kooistra), corne.kempenaar@wur.nl (C. Kempenaar).

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size of the treatment units (spatial units at which the vitality of the crop is sensed and herbicide rate is adjusted). When the size of treatment units is larger than the scale at which crop vitality varies, the herbicide rate for a treatment unit must be based on the "greenest" part of that treatment unit in order to achieve effective killing of the entire crop. This means that some parts will receive a higher herbicide rate than is necessary. Consequently, the amount of herbicide used decreases with the size of the treatment units until the size of the treatment units matches the scale at which crop vitality varies. An upper size of 1–2 m^2 has been suggested for the individual spatial units to be treated (Chancellor and Goronea, 1994; Solie et al., 1996). However, these authors investigated application of nitrogen, water, and herbicide for weed control. To our knowledge, there is no information in the literature on whether these results apply to PHK, nor is it known how large the effect of inter-field variation is. The second question relates to the cost of VRA PHK and the effort required to maintain the near sensing instrument, which is sometimes seen as an impediment to widespread deployment of a VRA PHK system.

Remote sensing may offer an insight to the first question, and an answer to the second one. Remote sensing provides an image of an entire field and can thus be used to assess the pattern of spatial variability, Further, these images become available for many fields at the same time, and thus provide a basis for studying inter-field variation. The cost of site-specific PHK may possibly be lower if remote sensing imagery is used to measure crop vitality, which would remove the need for an expensive near sensing instrument on each tractor. In this scheme, herbicide rates would be determined from the satellite image and an herbicide rate map would be uploaded to the spraying equipment to effect the treatment.

If the existing decision rules for PHK herbicide rate are to be driven with remotely sensed data, a correspondence must be established between the remote sensing measurement and the near-sensing measurement currently used. While remote sensing has been used extensively to monitor crop status, there are but few reports where a direct comparison between near-sensing and remote-sensing is made. In a study where NDVI of wheat was measured nearly simultaneously with the Ikonos satellite and with near-ground sensors, a strong correlation between both sets of measurements was found (Reyniers and Vrindts, 2006). Similarly, a good correlation was found between NDVI measured with a ground-based spectroradiometer and NDVI measured with a camera carried by a unmanned helicopter (Swain et al., 2007, 2010). In a series of experiments in which NDVI in maize and wheat was measured with Greenseeker and with the Yara N-Sensor, a good correlation between the output of both sensors was found (Tremblay et al., 2009). To our knowledge, there is no literature which compares WDVI from near-sensing and remote-sensing in potato.

In view of the above, the first objective of this paper is to establish a relationship between WDVI of potato derived from satellite imagery on the one hand and measured with hand-held or tractor-mounted equipment on the other hand. This relationship will be used to recommend a herbicide rate for PHK based on satellite imagery.

The second objective of this paper is to use satellite imagery to estimate the reduction in herbicide use for PHK as a function of the spatial scale at which herbicide rate is adjusted.

2. Materials and methods

2.1. Decision rule for haulm killing

A recommendation for the site-specific rate of the haulm killing herbicide Reglone (active substance: diquat dibromide (200 g L^{-1})) has been derived from experiments (Kempenaar et al., 2004) in which the vitality of the crop had been measured with the Cropscan reflectance meter (Cropscan Inc., Rochester MN, USA; see Table 1). The recommendation is:

$$D = \min[3.0, 0.38 \exp(4.9\,\mathrm{WDVI})] \quad (1)$$

where D is the herbicide rate (L ha^{-1}), min( ) is a function which returns the smallest of its arguments, exp( ) indicates exponentiation with base e, and WDVI (Weighted Difference Vegetation Index, $0 \le \mathrm{WDVI} \le 1$) is a vegetation index that combines a red and a near-infrared band (Clevers, 1989). Bouman et al. (1992) calculated WDVI using a green instead of a red band and showed that potato LAI and biomass are strongly correlated to WDVI. Following these authors

$$\mathrm{WDVI} = R_{v,810} - \left(\frac{R_{s,810}}{R_{s,560}}\right) R_{v,560} \quad (2)$$

where $R_{v,810}$ is the reflectance centred at 810 nm (near-infrared) from the vegetated scene, $R_{v,560}$ the reflectance at 560 nm (green) from the vegetated scene, $R_{s,810}$ the reflectance at 810 nm from bare soil, and $R_{s,560}$ the reflectance at 560 nm from bare soil. From here on, WDVI with subscript "cs" will be used to denote a

Table 1
Characteristics of sensors.

Type	Sensor	Characteristics
Hand-held	Cropscan	Nadir view. MSR87 has 8 wavebands of 20 nm width centred at 460, 510, 560, 610, 660, 710, 760 and 810 nm. MSR16 used in Valthermond has 16 wavebands of 20 nm width centred at 460, 490, 510, 560, 610, 670, 700, 720, 730, 740, 760, 780, 810, 870, 900, 970 and 1080 nm. MSR16 used in Reusel has 16 wavebands of 20 nm width centred at 490, 530, 550, 570, 670, 700, 710, 740, 750, 780, 870, 940, 950, 1000, 1050 and 1650 nm.
Tractor-mounted	Yara N-Sensor (passive)	Tractor-mounted, uses ambient light, oblique view, reflectance measured at 10 nm intervals between 450 and 900 nm (old "blue" model), or between 600 and 1100 nm (new "white" model)
Tractor-mounted	Yara N-Sensor (ALS)	Tractor-mounted, uses light source, oblique view, reflectance measured at undisclosed wavelengths
Satellite	Terra (EOS AM-1)	Imagery from the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) sensor on this satellite was used. Pixels of 15 m × 15 m. Wavebands B2 630–690 nm (red), 770–895 (NIR). Revisit frequency: every 16 days, though image recording can be more frequent due to steerable sensor.
Satellite	WorldView-2	Pixels of 1.8 m × 1.8 m. Wavebands B2 630–690 nm (red) and 770–895 (near-IR 1). Revisit frequency: 2–3 days in The Netherlands

measurement of WDVI obtained with a Cropscan reflectance meter; WDVI with subscript "sat" will be used to denote a measurement of WDVI obtained with a satellite.

2.2. Sensors

An overview of the sensors used in this work is given in Table 1. Two types of near-ground sensors and two satellites were used. One type of near-ground sensors were MSR87 and MSR16 radiometers (Cropscan Inc., Rochester, MN, USA). The Cropscan sensors have both upward- and downward looking photo diodes so as to enable immediate measurement of reflectance. The MSR87 has 8 elements whereas the MSR16 has 16 elements. Bandpass filters limit the wavelengths of the light that reaches the photo diodes. Cropscan measurements were used to calculate WDVI. Another type of near-ground sensor was the N-Sensor (Yara International ASA, Oslo, Norway). Both the passive N-Sensor which relies on ambient light, and the ALS N-Sensor which contains a light source, were used. An N-Sensor is typically mounted on the roof of a tractor and has an oblique view of the crop in four directions: to the left-front, left-rear, right-front and right-rear. In each direction, a roughly circular patch is viewed; the patches fall within a 15 m × 15 m area. Both the passive N-Sensor and the ALS sensor yield a vegetation index named S1. The S1 is a sensor-specific combination of wavebands so that the S1 of the passive N-Sensor cannot be expected to give the same value as the S1 of the N-Sensor ALS (pers. comm., Stefan Reusch, Yara). Details about which bands are used and how they are combined are not disclosed. However, it is known that the S1 measured above a bare soil should be very close to zero (pers, comm., Stefan Reusch, Yara). Please note that the S1 index is only an intermediate step in the procedure (see below) and use of this index does not limit the validity of the results presented in this paper to the Yara sensors.

Satellite imagery from the ASTER sensor of the Terra satellite and from the WorldView-2 satellite was used. Both the ASTER and Worldview-2 images were programmed exclusively for this study. The satellite images were atmospherically corrected and calibrated (converted to reflectance values) using the ATCOR software (version 8.0, ReSe Applications Schläpfer, Wil, Switzerland). The Red and NIR (Near Infra-Red) bands of the ASTER and Worldview-2 images are used to calculate the WDVI according to Clevers (1989):

$$\mathrm{WDVI} = R_{\mathrm{nir}} - aR_{\mathrm{red}} \quad (3)$$

where R_{nir} is the reflectance in the infra-red band, R_{red} the reflectance in the red band, and a is the slope of the line through a plot of NIR against Red reflectance values of approximately 200 bare soil pixels found on the image. These points were manually selected on the image. The images are manually geo-referenced to the Dutch national grid ("Rijksdriehoekstelsel") using a base map with a horizontal accuracy of around 1 m. Gridded images with a spatial resolution of 15 m for Aster and 1.8 m for WorldView-2 were made using nearest-neighbour resampling.

2.3. Datasets

Several datasets were used in which reflectance of potato was measured with one or more of the above-mentioned sensors. An overview of datasets used is given in Fig. 1. Basic agronomic information is given in Table 2.

Vredepeel dataset. On 7 September 2004, near-ground measurements were taken in a field of potato (cv. Asterix) on experimental farm "Vredepeel" in Vredepeel (51°32′26″N, 5°51′14″E) with a sandy soil. The above-ground biomass was dying at that time (code 91 on BBCH-scale). At 50 locations in the field, measurements were taken simultaneously with a Cropscan MSR87 and with a passive N-Sensor.

Wiski dataset. Wiski is a collaborative effort to adopt precision-farming by a group of commercial farmers in the vicinity of Dronten (52°31′N, 5°43′E). The Wiski farms are located on reclaimed land and the soil is a marine clay. In 2009 and 2010 measurements were taken by Wiski members with an N-Sensor ALS. ASTER imagery for the area in which the Wiski farms are located was available on 16 July and 19 August 2009 and on 20 August and 5 September 2010. N-Sensor measurements were taken on 20 July 2009 and on 23 dates between 17 June and 13 September 2010.

Lelystad dataset. Also located in the vicinity of Lelystad is the experimental farm "PPO-Lelystad". In 2009 and 2010 measurements were taken on several fields on this farm with a N-Sensor (passive). ASTER imagery for the area in which the PPO-Lelystad farm is located was available on 16 July and 19 August 2009 and on 20 August and 5 September 2010. N-Sensor measurements were taken on 19 August 2009 and on 8 dates between 19 August and 11 September 2010.

Valthermond dataset. In 2010 an experiment with various levels of N application was conducted on experimental farm "'t Kompas" in Valthermond (52°52′27″N, 6°56′33″E). The farm has a sandy soil with high level of organic matter. Plot size was 24 m × 30 m so that it was possible to take measurements with a (passive) N-Sensor which has a footprint of 15 m × 15 m. Cropscan measurements were taken at various points in the plots and are representative of a plot. WorldView-2 satellite imagery was available for 17 June 2010 (not coincident with Cropscan measurements). WorldView-2 pixels are 1 m^2. To minimize boundary effects, only those WorldView-2 pixels were selected for which the centre was located within 3 m of the centre of each plot.

Biddinghuizen dataset. In 2010 measurements were taken simultaneously with an N-Sensor ALS (software rev. <3.3) and with a Cropscan MSR87, in two fields on a commercial farm in Biddinghuizen (52°27′N, 5°42′E). The soil was marine clay on reclaimed land. The two fields contained plots with various N rate treatments. Plot size was 16 m × 25 m.

Reusel dataset. Measurements were made in 2010 on a field of a commercial farm on sandy soil near Reusel (51°21′42″N, 5°9′53″E). Plot size was 30 m × 30 m and various levels of N were applied. A Cropscan MSR16 was used for weekly reflectance measurements. WorldView-2 satellite imagery was available for 3 and 22 June 2010. To minimize boundary effects, only those WorldView-2 pixels were selected for which the centre was located within 3 m of the centre of each plot.

2.4. Data processing

In order to use Eq. (1) with satellite imagery, a relationship is needed which allows conversion of (satellite-derived) $\mathrm{WDVI}_{\mathrm{sat}}$ to (Cropscan-derived) $\mathrm{WDVI}_{\mathrm{cs}}$. The datasets contain no simultaneous measurements with Cropscan and ASTER that would make it possible to establish a direct relationship based on WDVI between the two kinds of measurements. However, the datasets do contain (a) a large number of simultaneous measurements of a N-Sensor (some with the passive version, some with the ALS version) and ASTER, (b) simultaneous measurements of Cropscan and N-Sensor, and (c) some simultaneous measurements of Cropscan and the high-resolution WorldView-2 satellite. Thus, first a relationship was established between Cropscan measurements and N-Sensor measurements using the Biddinghuizen, Vredepeel and Valthermond datasets, and next a relationship was established between N-Sensor measurements and ASTER using the Wiski and Lelystad datasets. These two relationships were then combined to establish a relationship between Cropscan measurements and ASTER measurements. The Cropscan-ASTER relationship was compared with the Cropscan-WorldView-2 relationship that could be established directly using the Valthermond and Reusel datasets.

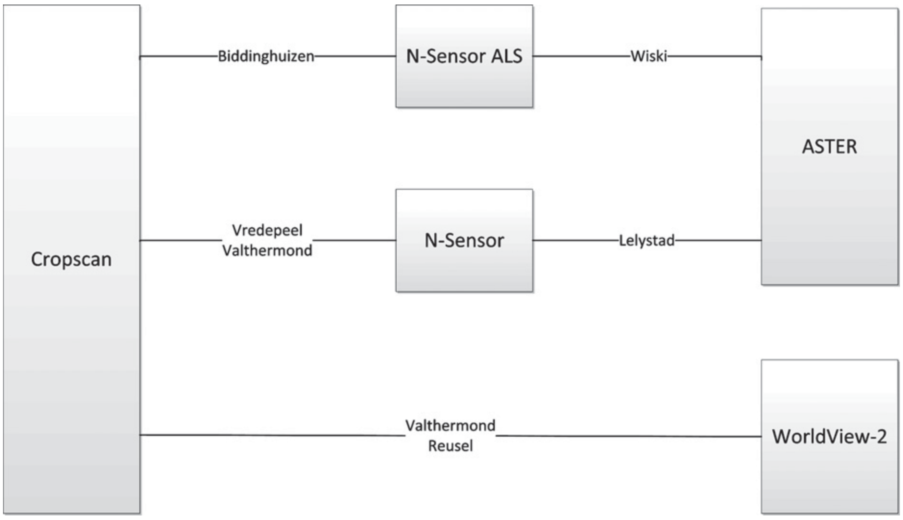

Fig. 1. Overview of sensors (rectangles) and datasets (connecting lines) used in this paper. The graph should be read as, for example: "The Biddinghuizen dataset was used to establish a relationship between values measured with the Cropscan and values measured with the N-Sensor ALS".

Satellite pixels were matched with N-Sensor measurements as follows. Satellite pixels measure 15 m × 15 m and are oriented on a rectangular grid whose axes are North-to-South and East-to-West. N-Sensor measurements are taken along the path of travel of the tractor on which the sensor is mounted and are individually georeferenced. The distance between two subsequent N-Sensor measurements depends on the driving speed of the tractor; typically, it varies between 1 and 2 m. An N-Sensor measurement and a satellite pixel are considered to represent the same location on the ground if the distance from the N-Sensor measurement to the centre of the satellite pixel is less than a threshold value calculated as:

$$[(x_{\text{N-sensor}} - x_{\text{pixel}})^2 + (y_{\text{N-sensor}} - y_{\text{pixel}})^2]^{0.5} < d \quad (4)$$

where ($x_{\text{N-Sensor}}, y_{\text{N-Sensor}}$) are the coordinates of the N-Sensor measurement ($x_{\text{pixel}}, y_{\text{pixel}}$) are the coordinates of the centre of a satellite pixel (both expressed in the rectangular coordinate system in use in The Netherlands), and d is the threshold value for inclusion (m). When two or more N-Sensor measurements are matched with a single satellite pixel, the average of their values is taken. When the parameter d in Eq. (4) is set to a small value (for example, 5 m), some satellite pixels which lie close to the path of the tractor may nevertheless remain unmatched with any N-Sensor measurements. When d is set to a large value, the N-Sensor measurement and the satellite pixel can no longer be assumed to represent the same location on the ground; also, a single N-Sensor measurement may be matched with two or more satellite pixels. ASTER pixels are 15 m × 15 m, so that the distance from the centre to one of the corners is 10 m. Here d = 10 m was used, which is a trade-off between a smaller value which would result in a significant number of pixels remaining unmatched with N-Sensor measurements, and a larger value which would include N-Sensor measurements that do not coincide with the satellite pixel.

2.5. *Effect of spatial scale of application on reduction in herbicide use*

The effect of the size of treatment units on the amount of herbicide used was investigated using ASTER imagery of 13 fields, taken close to the time for haulm killing. First, for each pixel (15 m × 15 m) of each image, herbicide dosage was calculated using Eq. (1) and the relationship between $WDVI_{sat}$ and $WDVI_{cs}$ developed above. The average dosage for each field was calculated as the average of the dosage for the individual pixels belonging to that field. This average dosage represents the minimum amount of herbicide necessary to completely kill the potato crop.

In the next step it was investigated how much more herbicide would be necessary to treat each field at larger spatial scale of sensing and application. To this end, the pixels within a field were aggregated into rectangular blocks by combining adjacent pixels (1 × 2: 2 pixels adjacent in North–South direction; 2 × 1: 2 pixels adjacent in East–West direction; 2 × 2, 2 × 3, 3 × 2, etc.). The dosage of each block was determined by the pixel in that block with the highest WDVI. For each field and for each method of blocking, the average dosage was calculated as the average of the dosage for the blocks.

3. Results

Vredepeel. The relationship between $WDVI_{cs}$ and S1 (measured with a passive N-Sensor) is given by $WDVI_{cs}$ = 0.01942 S1 (Fig. 2). The intercept of an unconstrained regression was not significant (P = 0.72).

Valthermond: The spectra measured in 2010 with Cropscan on the bare soil plots indicated that the plots had not been kept completely free of weeds. Measurements in 2011 in the same field yielded a value of 1.7 for $R_{s,810}/R_{s,560}$. This value was used to

Table 2
Details about crops in datasets.

Dataset	Year(s)	Soil	Cultivar	Treatments
Vredepeel	2004	Sand	Asterix	Local practice
Wiski	2009, 2010	Marine clay	Milva	Local practice
Lelystad	2009, 2010	Marine clay	Milva	Local practice
Valthermond	2010	Sand (high SOM)	Seresta	N levels
Biddinghuizen	2010	Marine clay	Nicola, Milva	N levels
Reusel	2010	Sand	Fontane	N levels

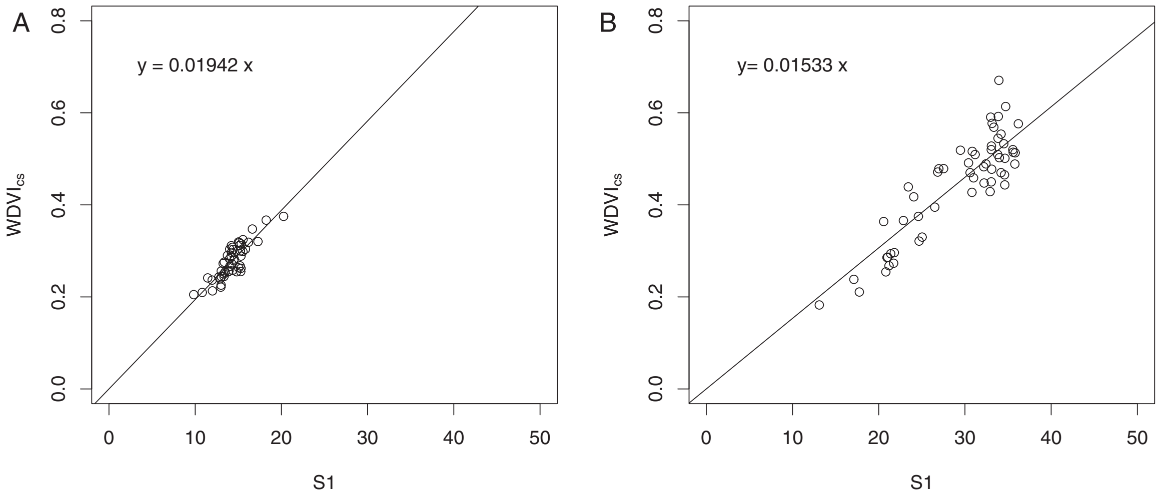

Fig. 2. Relationship between S1 measured with the passive N-Sensor and WDVI measured with Cropscan. (A) Data from 50 locations on a field at Vredepeel, 7 September 2004. (B) Data from Valthermond in 2010.

calculate $WDVI_{cs}$. The relationship between $WDVI_{cs}$ and S1 (measured with a passive N-Sensor) is given by $WDVI_{cs} = 0.01533$ S1 (Fig. 2). Unconstrained regression yielded a non-significant intercept ($P = 0.25$).

Data from Vredepeel and Valthermond (both passive N-Sensor) were combined. A regression line fitted through both sets of data showed a significant intercept ($P < 0.01$). This regression was influenced by the points from Vredepeel which were taken on a single date and are thus clustered, whereas the points from Valthermond were taken throughout the growing season. Because of this and also because theory predicts a relationship through the origin, a regression line was fitted through the origin: $WDVI_{cs} = 0.01604$ S1.

Biddinghuizen. The relationship between $WDVI_{cs}$ and S1 (measured with a N-Sensor ALS) is shown in Fig. 3. There appears to be a time- or growth-stage dependent element in the relationship between WDVI and S1. The earliest measurements show S1 to be approx. 20, below the regression line. In subsequent measurements both S1 and $WDVI_{cs}$ increase and data points approach the regression line. In the second half of July and August, both S1 and $WDVI_{cs}$ decrease, represented by the data points above the regression line. A regression line was drawn through the origin, because of theory

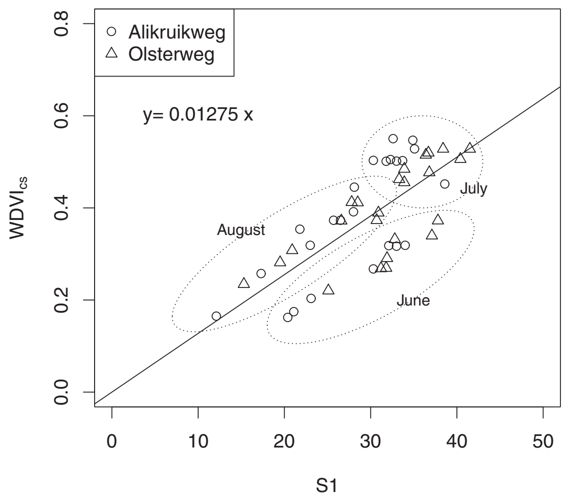

Fig. 3. Relationship between S1 measured with the N-Sensor ALS and WDVI measured with Cropscan. Data from two fields ("Alikruikweg" and "Olsterweg") at Biddinghuizen. The ellipses approximately indicate data points taken on 15 and 22 June; on 6, 13 and 27 July; and on 3, 10 and 24 August.

(as explained in the first paragraph of this section) and because the intercept was not significant. The relationship between ASTER-derived $WDVI_{sat}$ and (passive) N-Sensor S1 is shown in Fig. 4a, the relationship between ASTER-derived $WDVI_{sat}$ and N-Sensor ALS S1 is shown in Fig. 4b. In both cases a linear regression through the origin was fitted to the data. For the passive N-Sensor, the vast majority of (approx. 1200) data points is well described by the regression, although several dozen data points lie significantly above the line. Upon investigation, it was found that these points correspond to a physical feature on the ground, such as a tower for a power line or a field boundary.

Satellite and Cropscan are related through N-Sensor by substituting $S1 = 50.8 \times WDVI_{sat}$ (Fig. 4a) into $WDVI_{cs} = 0.01604 \times S1$ to obtain:

$$WDVI_{cs} = 0.815 \quad WDVI_{sat} \tag{5}$$

Combination of Eqs. (1) and (5) yields the following equation for herbicide dosage:

$$D = 0.377 \quad \exp(4.00 \quad WDVI_{sat}) \tag{6}$$

Alternatively, satellite and Cropscan are linked through N-Sensor ALS by substituting $S1 = 73.12 \times WDVI_{sat}$ (Fig. 4b) into $WDVI_{cs} = 1.275 \times S1$ to obtain:

$$WDVI_{cs} = 0.924 \quad WDVI_{sat} \tag{7}$$

Combination of Eqs. (1) and (7) yields the following equation for herbicide dosage

$$D = 0.377 \quad \exp(4.58 \quad WDVI_{sat}) \tag{8}$$

Eqs. (6) and (8) are similar and there is no information which would lead us to prefer either result. Thus, it seems reasonable to average the results and use the following:

$$WDVI_{cs} = 0.883 \quad WDVI_{sat} \tag{9}$$

$$D = 0.377 \exp(4.34 \quad WDVI_{sat}) \tag{10}$$

The dataset contains one WorldView-2 image which shows the experiment at Valthermond. The image was acquired on 17 June 2010. The closest dates for which Cropscan measurements at Valthermond are available are 14 June and 23 June. Cropscan and WorldView-2 derived $WDVI_{sat}$ are shown in Fig. 5. $WDVI_{sat}$ measured on 17 June and expressed as $WDVI_{cs}$ with the help of Eq. (9) is lower than the Cropscan measurements of 14 June – but this is to be expected because there is a difference of three days

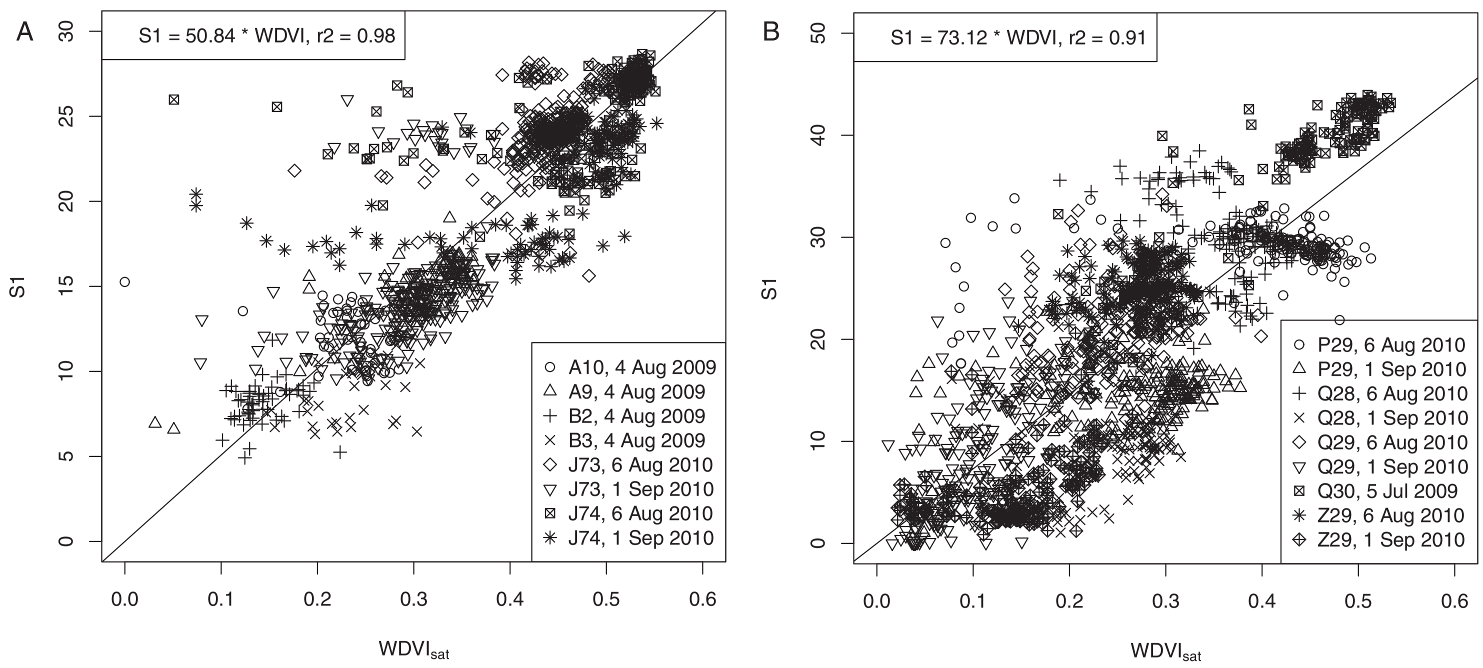

Fig. 4. Relationship between $WDVI_{sat}$ and N-Sensor S1 as measured by (A) Passive N-Sensor, and (B) N-Sensor ALS.

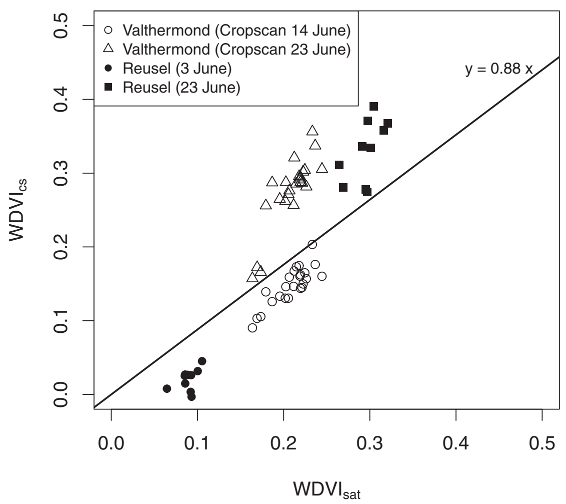

Fig. 5. Comparison between WDVI measured with Cropscan and WDVI measured with WorldView-2 satellite. Data points represent measurements from the Valthermond and Reusel datasets; the line represents the relationship of Eq. (10). Valthermond: WorldView-2 image of 17 June 2010 is matched with Cropscan data taken on 14 and 23 June. Reusel: WorldView-2 image of 2010-06-03 is matched with Cropscan data taken on 2010-05-31, and WorldView-2 image of 2010-06-22 is matched with Cropscan data taken on 2010-06-23.

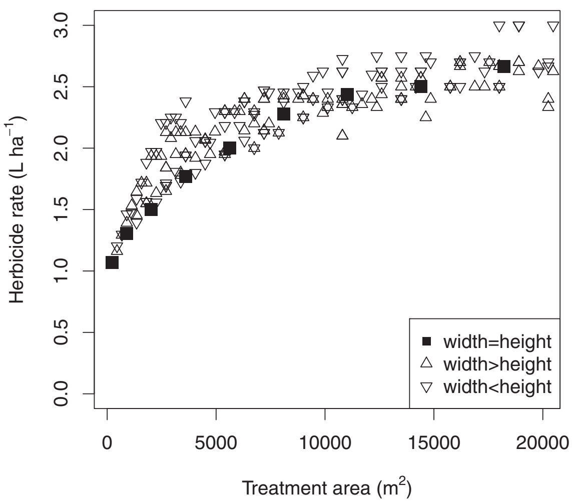

Fig. 6. Average application rate of the haulm killing herbicide Reglone as a function of the size of the area on which crop reflection is measured and herbicide rate is adjusted. Closed symbols indicate square treatment units; open symbols indicate treatment units that are rectangular but not square. See text for full details of the followed procedure.

between the measurements, at a time when the crop was growing rapidly. In the same fashion, $WDVI_{sat}$ measured on 23 June and expressed as $WDVI_{cs}$ with the help of Eq. (9) is higher than the Cropscan measurements of 14 June.

The dataset contains two WorldView-2 images which show the experiment at Reusel. These images were acquired on 3 and 22 June 2010. Cropscan measurements were made on 31 May and 23 June. The data are shown in Fig. 5 along with the data from Valthermond. The WDVI measured with Cropscan on 31 May was smaller than the WDVI measured with WorldView-2 on 3 June. This is explained by the rapid increase in LAI and above-ground biomass of the crop in this early stage of the growing season. WDVI measured with Cropscan on June 23 was larger than the WDVI measured with WorldView-2 on 22 June.

The satellite images make it possible to determine the effect of the spatial scale of sensing on the reduction in herbicide use. A satellite image covers the entire field. This is unlike near-sensing measurements, which at best measure many locations in a field, but never the entire field. The size of ASTER pixels is 15 m × 15 m, which is the smallest spatial unit that can be analysed with these data. When for each pixel the appropriate herbicide rate is determined according to Eq. (1), then the entire field is adequately treated while the minimum possible amount of herbicide is used. For example, for field Q29 (near Lelystad) on 5 September 2010, this amount was 1.0 L ha^{-1} (Fig. 6).

When two or more adjacent pixels are taken together to form larger spatial units, and these larger spatial units are treated (according, again, to Eq. (1)), then the amount of herbicide used will be based on the "greenest" pixel in each block, and will thus in most cases be larger than when based on individual pixels. The resulting increase in field-averaged herbicide rate with block size is shown in Fig. 6. Please note that the maximum rate according to Eq. (1) (3.0 L ha^{-1}) is reflected in the figure.

The above procedure was executed for all thirteen fields for which ASTER imagery was available at or near the time of haulm killing. Thus, for each blocking size (including blocks of exactly 1 pixel), thirteen average herbicide rates were obtained, namely one rate for each field. For each blocking size, these thirteen rates were ordered from small to large and a probability of 1/13 was assigned to each. Fig. 7 shows the cumulative probability plot which was obtained by plotting herbicide rate on the horizontal axis, and cumulative probability (always a multiple of 1/13) on the vertical axis.

4. Discussion

The results presented in this paper indicate that there is a strong and linear relationship between $WDVI_{sat}$ and $WDVI_{cs}$. The majority of the approx. 1200 points in Fig. 4 are close to the regression line. Several dozen outliers are present for which $WDVI_{sat}$ is lower (less biomass) than expected. Upon investigation, it was found that these points correspond to a physical feature on the ground, such as a tower for a power line or a field boundary. Crop growth is depressed due to shadowing in the vicinity of a tower. Likewise, crop growth is often less near a field boundary. Also, due to unavoidable uncertainty in georeferencing, a satellite pixel which is thought to be fully

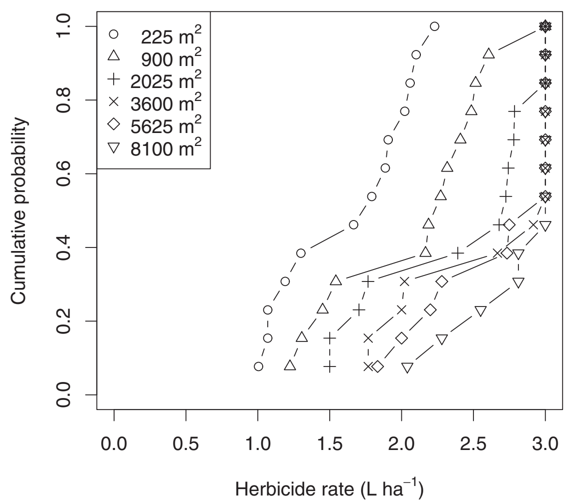

Fig. 7. Cumulative probability of average application rate of the haulm killing herbicide Reglone, as a function of size of the treatment unit (square treatment units only). For an example of how the graph is read, consider the line for a treatment unit of 225 m^2. The 8th point from the bottom represents a cumulative probability of 8/13 = 0.62 and an herbicide rate of 1.8 L ha^{-1}. This can be expressed as follows: when the spatial unit of application is one pixel (15 m × 15 m), then the field-averaged herbicide rate will be 1.8 L ha^{-1} or less in 62% of the fields.

inside the field may in fact straddle the field boundary. Outside the field there is less biomass than inside the field, thus a pixel that is partially outside the field will have a lower $WDVI_{sat}$ than a pixel inside the field. A near-ground sensor is always pointing inside the field and the error in georeferencing a near-ground measurement derives from uncertainty in the GPS measurement (order of magnitude: cm's). In summary, the outliers can be explained and do therefore not invalidate the general relationship between $WDVI_{cs}$ (via S1) and $WDVI_{sat}$. A further demonstration of the robustness of the relationship between $WDVI_{cs}$ and $WDVI_{sat}$ is given by the fact that the relation derived using ASTER data also describes WorldView-2 data well (Fig. 5).

The conditions under which reflectance is measured are very different for a near-sensing instrument and a satellite. The systems differ in wavebands used (both centre wavelength and width of the waveband), the medium between sensor and object (at most a few meters of air, versus an atmosphere potentially laden with dust and water vapour), and spatial resolution. In addition, sometimes there is a difference of a few days between ground-based and satellite-based measurement. Thus, while in some cases a good correlation has been found between a near-sensing measurement and remote measurement (Reyniers and Vrindts, 2006; Swain et al., 2007, 2010), it is not to be expected that a vegetation index such as WDVI measured with a near-sensing instrument will be numerically equal to WDVI measured with a satellite. However, it is to be expected that there will be a certain amount of noise in the relationship (Fig. 4). This paper provides no data, which would allow to determine the relative contribution of the disturbing factors mentioned above.

With the relationship between $WDVI_{cs}$ and $WDVI_{sat}$, satellite imagery can be used to map WDVI for many fields and for every square meter of each field. This is in contrast with near-sensing equipment which, if hand-held, will be used to measure at most dozens of points in a field, or which, if mounted on a tractor, will be used to measure only in the vicinity of the tractor's path. In this paper, detailed maps of WDVI of thirteen commercial fields were created and analysed to determine a relationship between size of the treatment units and the field-averaged amount of herbicide needed for PHK. The analysis showed that a reduction in the size of the treatment units resulted in a reduction in herbicide use for the whole field. A treatment unit size of 6×6 pixels ($90\,m \times 90\,m \sim 1$ ha) resulted in a uniform rate of $3\,L\,ha^{-1}$ in most fields. Smaller treatment units led to a reduction in herbicide use relative to current practice ($3\,L\,ha^{-1}$). Treatment units of 2×2 pixels ($30\,m \times 30\,m$) correspond closely to the units that can be treated with slightly modified conventional equipment; with units of this size, a reduction of 30% relative to current practice was calculated for at least 50% of the fields. With treatment units the size of a single satellite pixel ($15\,m \times 15\,m$) a reduction of 50% in at least 50% of the fields was calculated. It is likely that even higher reductions could be achieved by further reducing the size of treatment units. The data presented do not allow us to calculate the maximum reduction possible. This paper can therefore neither refute nor confirm the statement $1–2\,m^2$ is the upper size of treatment units (Chancellor and Goronea, 1994; Solie et al., 1996).

The analysis of images for 13 fields shows that reduction in herbicide use relative to current practice approaches the 50% that is mentioned by (Kempenaar et al., 2010a). An explanation for the slightly smaller reduction in herbicide use than reported by (Kempenaar et al., 2010a) may be due to some of the satellite images having been taken relatively early in relation to the moment of haulm killing.

The analysis summarized in Fig. 7 can be used to determine the spatial unit of application that is needed to reach a goal of reduction in herbicide use. If, for example, the goal is to use at most $2.0\,L\,ha^{-1}$ in 50% of the fields, then a spatial unit of between $15\,m \times 15\,m$ and $30\,m \times 30\,m$ would be required.

In Fig. 7, the horizontal separation between two lines is a measure of the reduction in herbicide use that can be realized by reducing the size of the spatial unit of application. It can be seen in that by decreasing the size of spatial units from $30\,m \times 30\,m$ to $15\,m \times 15\,m$ would result in herbicide savings of approximately $0.5\,L\,ha^{-1}$.

5. Conclusion

A relationship was established between near-sensing and remote-sensing of a vegetation index for potato which works well for two different satellites. This result enables satellite-based recommendation of herbicide rate for potato haulm killing. The reduction in herbicide use that may be obtained with VRA was shown to be dependent on the size of the treatment unit. With treatment units not larger than $30\,m \times 30\,m$, a reduction in the use of herbicide of 50% is possible, with obvious advantages from economic and environmental points of view.

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